

SIMA Austral: An operational information system for managing the Chilean aquaculture industry with international application

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ABSTRACT

The Integrated Management System for the Aquaculture (SIMA in Spanish) is a comprehensive interoperable information and modelling platform that has been developed to provide the Chilean Aquaculture industry and government agencies with access to improved environmental intelligence allowing them to make better informed strategic and operational decisions. *SIMA* is built upon an integrated system of biophysical production data, catchment and coastal-marine models, visualisation, reporting and risk-based decision support tools. This communication briefly describes the *SIMA* architecture and components and provides examples of applications of how it can be used to inform policy and management decisions, and discusses challenges and key learnings and considers future developments and applications.

ARTICLE HISTORY

Received 26 September 2018
Accepted 10 June 2019

KEYWORDS

Aquaculture; modelling; forecasting; real-time; operational; information's system; sustainability; risk-based management

Introduction



Aquaculture is the fastest growing food producing sector in the world, with a global aquaculture production in 2016 of 110.2 million tonnes, an estimated value of US\$243.5 billion and employing ~ 19.3 million people (FAO 2018a). Given this growth, there is a great expectation that aquaculture – enabled by technical innovation that will further increase resource efficiency – will bridge the future global supply-demand gap for aquatic food (Waite et al. 2014). In this regard, aquaculture is considered a positive means of addressing several of the UN sustainable development goals (SDGs) adopted in 2015 (United Nations 2015) – including ending poverty (SDG 1), ensuring universal food security (SDG 2), good health outcomes (SDG 3), employment and economic growth (SDG 8) and sustainable marine ecosystems (SDG 14).


However, aquaculture must also overcome a number of challenges that threaten its operation and sustainability and the surrounding environment in which it operates, such as eutrophication; climate-related extreme events and changing habitat suitability; ocean acidification; the increasing occurrence and severity of algal

blooms and red tides; and outbreaks of parasitic, bacterial and viral diseases that have led to high mortalities, interrupted production cycles, massive economic losses, unemployment and supply interruptions that affect markets and prices (Quiñones et al. 2019).

To ensure the long-term health and prosperity of the industry it is now recognised that four facets of sustainability – social, economic, environmental, and governance – will need to be addressed. Carrying capacity needs to be defined at a regional level and in doing so needs to recognise the many interconnected forms (McKindsey et al. 2006; Ross et al. 2013): *physical* (limits on suitable space available), *production* (based on operational details), *ecological* (broader environmental impacts on water quality and the food webs surrounding farms), *economic* (dictates when the industry is profitable) and *social* (details when the industry is considered socially acceptable by the broader community).

Best-practice from around the world (e.g. Norway, www.barentswatch.no; BlueBridge, <http://www.bluebridge-vres.eu>) indicates that a combination of industry's green narratives with integrated-tiered information

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 Supplemental data for this article can be accessed <https://doi.org/10.1080/1755876X.2019.1636606>

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delivery systems and a hierarchical risk assessment platform is an effective means of ensuring that aquaculture does not breach these many dimensions of carrying capacity and has been demonstrated to provide countries such as Norway with a market advantage (Fløysand and Jakobsen 2017; Asche et al. 2018). Such decision support tools combined with databases, information services and underpinned by various models (e.g. epidemiological, statistical, environmental and system-wide) help to create tools that can communicate the current status and trends – derived from public and industry data – along with predicted future states to inform management decisions and to address strategic planning scenarios.

*SIMA Austral*¹ is such an information system (Steven et al. 2018). It was commissioned by the Chilean government in 2015, to address the sustainability and competitiveness of the still growing USD\$3.5 billion Chilean aquaculture industry of the Austral region (Patagonia), which focuses mainly on the production of salmon (~90% of production, >663,000 tonnes in 2016), but also includes mussels, seaweed, oysters and abalone. This Industry has been challenged by disease outbreaks, most notably in 2007 when an outbreak of viral Infectious Salmon Anaemia (ISA) led to the collapse of salmon production resulting in the loss of 400,000 tonnes of fish, and up to 20,000 jobs (e.g. Mardones et al. 2009; Iizuka and Katz 2017). More recently, the occurrence of harmful algal blooms in early 2016 and 2018 have caused massive losses and dire economic consequences for the industry. It has been estimated that more than 1 million salmonids escape each year, mainly due to weather conditions and technical and operational failures of net-pens, leading to the establishment of self-sustainable populations resulting in the predation of, and disease and pathogen transfer to, native fish fauna (Sepúlveda et al. 2013).

Further, the excessive use of antibiotics by Chilean industries to combat these diseases has raised concerns as to the accumulated long-term impact on the marine environment (Buschmann et al. 2012), but also economically has led to lower retail prices and consumption of Chilean salmon internationally. Thus, local trust in the industry has been eroded and the social licence to operate (SLO) has become a significant issue, undermining broader support for the industry's operations and creating significant tension (Chávez et al. 2019). Nevertheless, the industry continues to expand further into southern Patagonia with total production forecast to increase to 1.2–1.3 million tonnes, with exports in excess of US \$6.5–7 billion and employment of 70,000–90,000 workers (Wurmann 2017).

SIMA was developed over a 3-year period by a multi-disciplinary team of more than 20 scientists, who engaged on a regular basis with key government,

industry and research stakeholders. *SIMA* became fully operational in January 2019 and delivers a range of products, to inform operational, reporting, incident response and scenario planning requirements (Steven et al. 2018). This communication summarises the architecture and components and describes existing applications of *SIMA*, discusses challenges and key learnings, both technical and from an end-user perspective, as well as considering future developments and applications.

SIMA architecture and components

SIMA is built upon an integrated system of data, physical and socioecological marine models, reporting, visualisation, and decision support tools (Figure 1) that enable users through a web-based dashboard to run a range of regulatory and non-regulator reports²; access risk-based tools for strategic and tactical planning and for incident response such as disease outbreaks that inform the assessment of various carrying capacities (Figure 2). *SIMA* spans Patagonian Chile – Los Lagos, Aysén and Magallanes regions – an area of ~ 300,000 km² (Figure 3).

The information delivering this functionality is derived from production and environmental data sourced both from within and external to the *Servicio Nacional de Pesca y Acuicultura* (SERNAPESCA), and coupled with regional-scale environmental (hydrodynamic, biogeochemical, sediment and stream flow) and socioecological models that include statistical, process and agent-based approaches. This information is delivered directly as data layers, but also via a hierarchical Ecological Risk Assessment framework originally developed in Australia (Hobday et al. 2011; Plagányi et al. 2011; Williams et al. 2011; Zhou et al. 2016; Hornborg et al. 2018), that is now the basis of risk assessments for Australian federal fisheries (AFMA 2017). It has also been applied in various forms to other fisheries around the world, including Canada (Martone et al. 2015), USA (Gaichas et al. 2018), the EU (Piet et al. 2015) and the International Commission for the Conservation of Atlantic Tunas (ICCAT; Cortés et al. 2015). The framework allows for a range of rapid strategic assessments, data-driven evaluations and in-depth quantitative analyses and modelling at different points in the planning and production³ management cycles (Figure 4(a)).

SIMA has been developed in close cooperation with SERNAPESCA staff (primarily from their animal health and environmental departments, and regional offices) to define – via user stories developed during one-on-one interviews and group sessions – the structure and functionality of *SIMA*. Similarly, the content of the models – and the definition of the scenarios to be explored using the models – was done in consultation with experts (including veterinarians, aquaculture and fishing

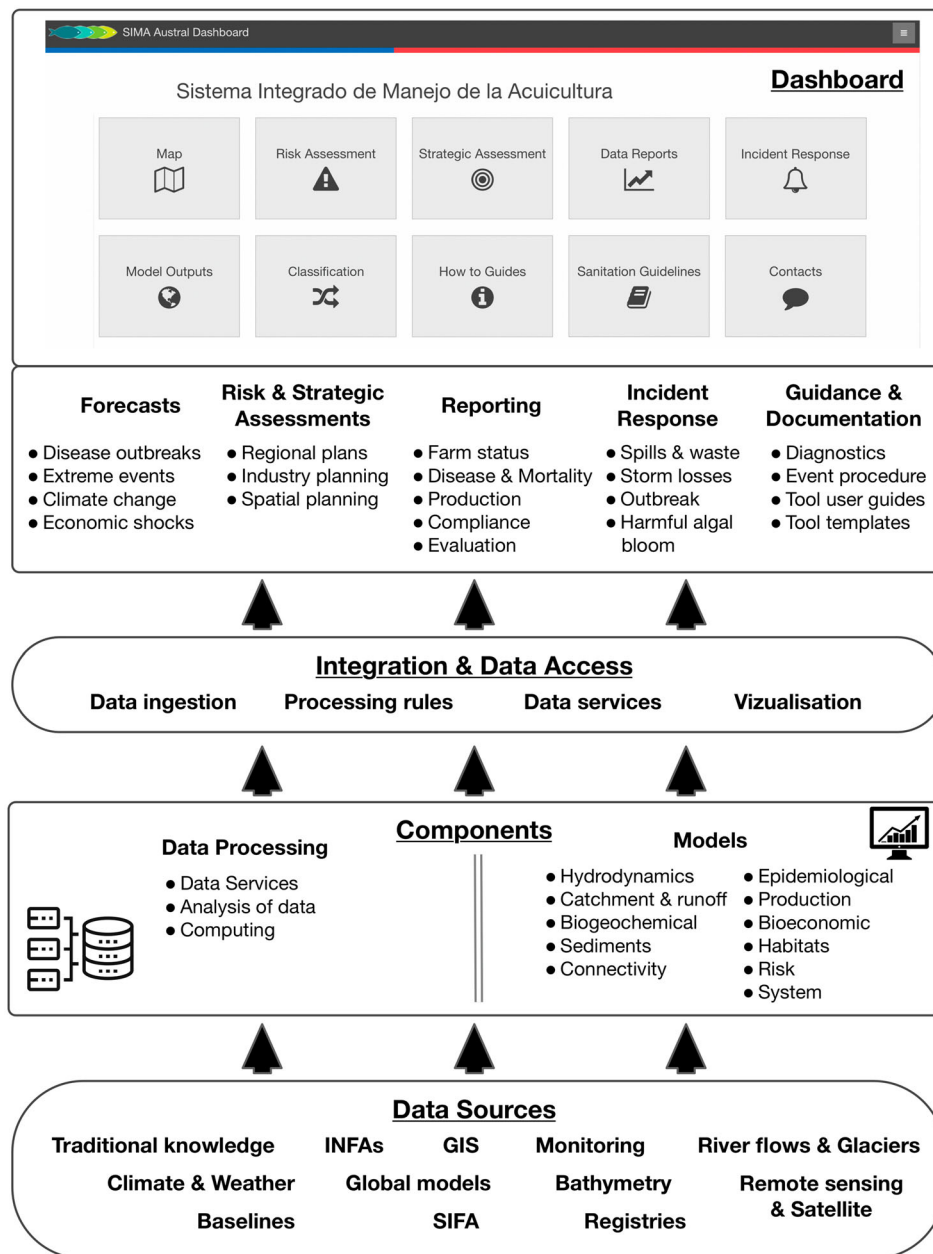


Figure 1. Conceptual diagram of SIMA information platform showing user-level functionality and the SIMA model and databases to be implemented.

industries and their regulators, indigenous communities, regional government officials and NGOs) in the three regions using a qualitative modelling approach of Dambacher et al. (2003). This information was supplemented by discussions with Australian aquaculture operational and epidemiological experts and an extensive review of available literature on each aspect of aquaculture; production, economics, ecological interactions, environmental conditions and interactions with management and society.

Below, we will briefly outline the contents of the different components of the SIMA platform before providing some illustrative examples of its application. Space

precludes an exhaustive description of the model content, data sources and skill metrics. Interested readers are referred to the supplemental material online for a table that summarises model content, forcing variables and data sources, validation status and technical references.

SIMA systems models

The individual components (sub-models) of the *SIMA Systems model* (bottom grey panel of Figure 5(b)) draw on data layers from other parts of *SIMA* (both models and data sources). The sub-models can be used as standalone

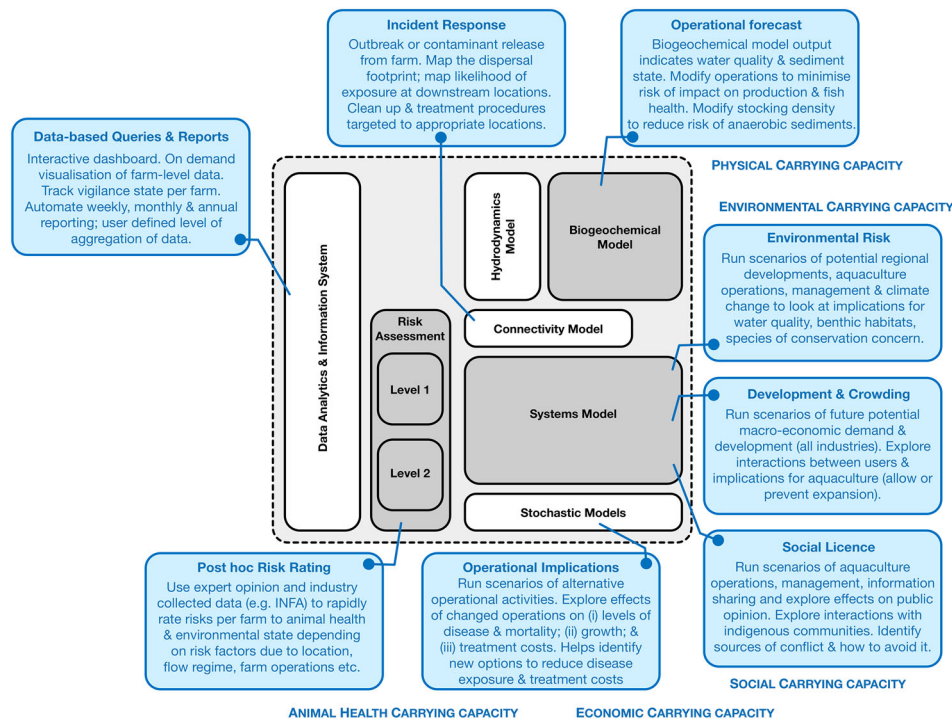


Figure 2. Application of SIMA components to use cases defined by carrying capacity.

components (e.g. to consider epidemiological or economic questions) or can be coupled in a modular way – supplemented by simple representations of non-aquaculture industries and the ecosystem – to form a systems model that encapsulates the entire regional system. The output of the systems model provides insight on potential strategic risks across the socioecological system, including responses to potential market, management or environmental scenarios that have been defined by the users (Fulton et al. 2018). Further details of all components and sub-models are provided in the supplemental material.

Farm-scale epidemiological and economic models

At the heart of the systems model is a spatially implicit ‘farm-scale’ epidemiological model, which is a statistically-derived probabilistic model that simulates fish growth, mortality and disease dynamics. The model parameters and transition probabilities between infection states have all been directly estimated (at a regional scale) from weekly data reported by industry to SERNA-PESCA between August 2010 and September 2017 (Richards and Fulton 2018).

The model simulates dynamics for three species – Atlantic salmon (*Salmo salar*), Coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*Oncorhynchus mykiss*) – and two of their common diseases, Salmonid Rickettsial Septicemia (SRS) and bacterial kidney disease (BKD). The user defines the region, number of farms within the production

neighbourhoods,⁴ species mix and farming practices (size at stocking, time of year when production begins, period over which fish are put in the water, species mix across the neighbourhood, fallow period, etc.). The model outputs growth, fish survival, total production and predicted disease prevalence as the production cycle progresses.

The economic model is a simple cost model, parameterised with a typology of business operation behaviours, that is tied directly to the farm-model to provide estimated costs and revenue (van Putten et al. 2018). This model encapsulates growth costs (smolt, feed, labour, sanitary and animal health treatments, leases, insurance and other overheads, harvesting, management costs such as observation, sampling, enforcement and associated reporting), price and operator structure (number and location of centres, volume and type of production, ownership and how that influences production and treatment regimes, and degree of integration). This level of understanding is important for delivering maximum economic efficiency, but also for making sure operations do not exacerbate disease risks and treatment costs, as Chilean salmon producers used more than 380 tonnes of antibiotics in 2016 alone, making antimicrobial resistance a real concern (Miranda et al. 2018).

Regional models

The regional systems model (Fulton et al. 2018) embeds the farm and economic model within the broader

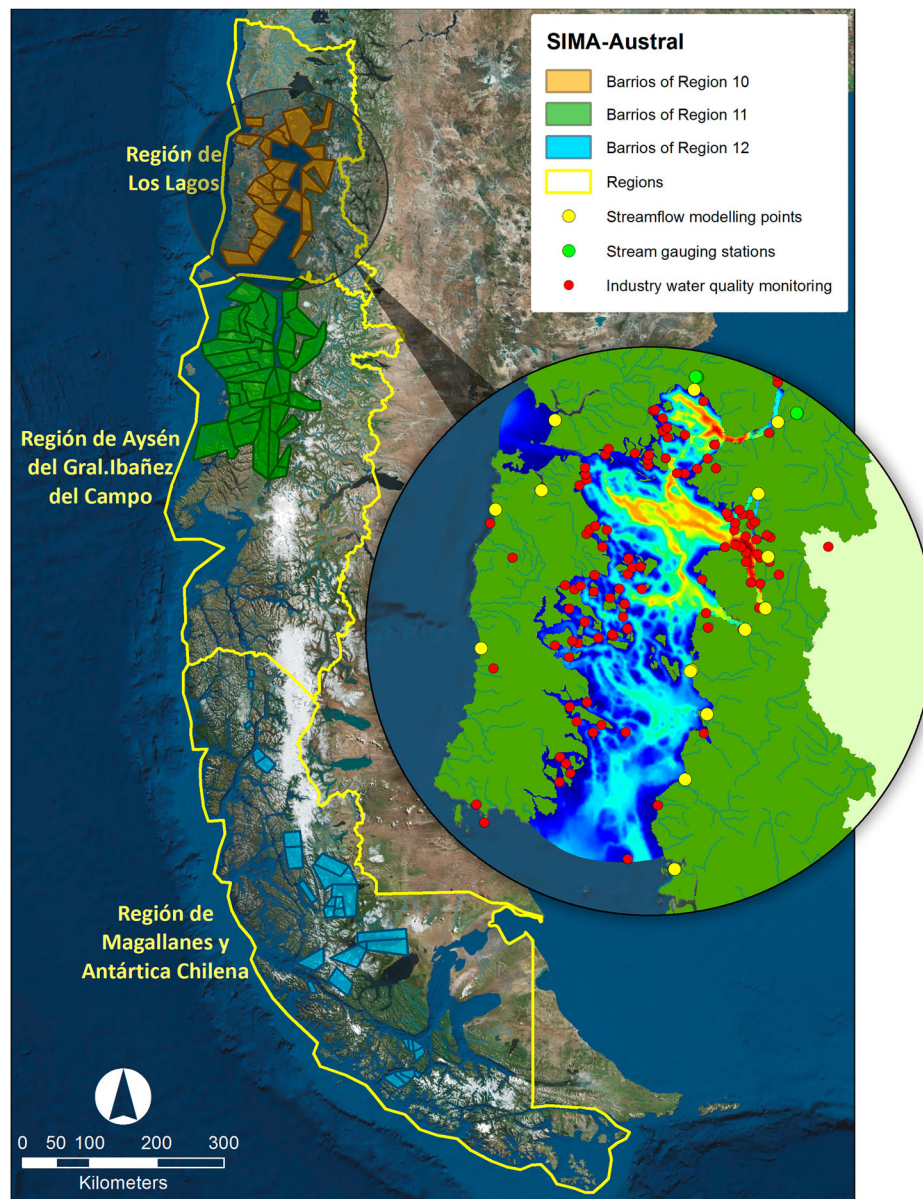


Figure 3. Map of southern Chile showing the extent of environmental and ecosystem models, and the occurrence of salmonid and mussel farming leases. The inset of the Los Lagos Region also shows stream gauge and water quality monitoring stations.

socioecological system, linking them with more than 20 other numerical models including: simple time series forcing, including of economic demand; qualitative networks (social aspects); statistical models (e.g. epidemiology); process-based analytical models (e.g. age-structured metapopulation models for wild fish stocks); and an agent-based representation of large marine mammals such as sealions and blue whales (Figure 4, supplemental material).

The conceptual structure of the model is modified from Engelen et al. (1997) and uses a cellular automaton to track the marine habitats; the abundance of the wild fish stocks (hake, sardine, urchin, crab and wild salmonids); the adjacent marine and terrestrial non-aquaculture industries (tourism; commercial, artisanal and indigenous

fishing; farming; plantations; logging, mining; and urban retail and services); as well as terrestrial vegetation types.

The aquaculture production centres, settlements, human population (labour force and general community) and marine mammals (sealions and blue whales) are represented using an agent-based modelling approach. This approach tracks the individual behaviour and state of these components. The overall demand for each sector and the representation of the terrestrial components is based on Fulton et al. (2017), modified to reflect local decision-making and operational practices. The aquaculture component of the systems model takes the farm-scale model and replicates it per farm site and tracks its neighbours and connections to other farms, settlements, transport routes and processing plants.

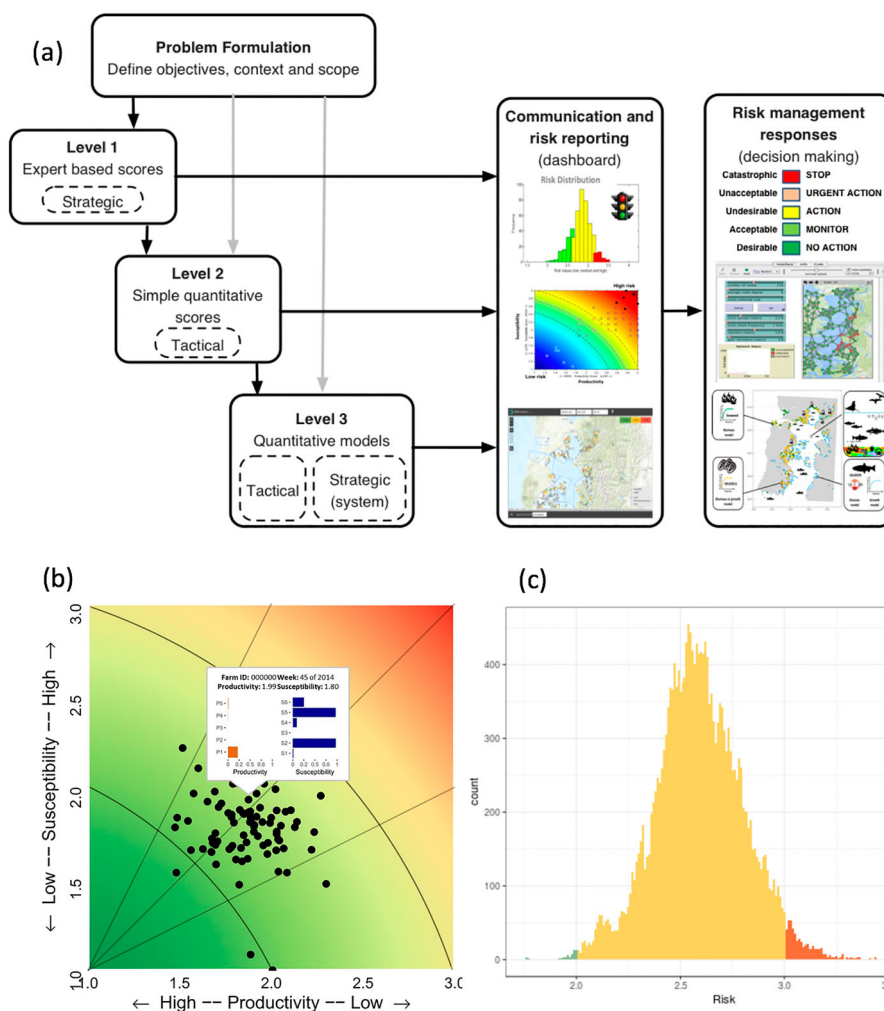


Figure 4. Schematic of the three-tiered risk assessment framework implemented for SIMA Austral, showing the two levels of assessment – semi-quantitative (using simple metrics by impact factors) and the fully dynamic quantitative models and the various levels of responses and outputs.

Outputs from this model include maps and time series for each major indicator, such as biomasses per stock, biodiversity, fish catch, aquaculture production, disease levels, production per industry, population, human footprint, income and revenue.

Model parameterisation and calibration was performed using information from Instituto de Fomento Pesquero (IFOP), Subsecretaría de Pesca y Acuicultura (SUBPESCA), SERNAPESCA, other Chilean national government departments via their geospatial infrastructure network IDE Chile,⁵ and regional governments. Data input and Validation procedures are further summarised in the supplemental material.

Environmental models

The SIMA *Environmental model* (top half of Figure 5(a)) is an implementation of the CSIRO Environmental Modelling Suite (EMS) that comprises a hydrodynamic

model SHOC (Sparse Hydrodynamic Ocean Code; Herzfeld 2006; Herzfeld et al. 2018) – driven at the catchment boundary by a purpose-built rainfall-snowmelt-runoff model – that is coupled to sediment (Margvelashvili 2009) biogeochemical and spectral optics models (Baird et al. 2016). This environmental modelling suite delivers data and maps of key oceanographic and ecological conditions, but is currently only fully implemented for the Los Lagos region due to constraints on appropriate available fine-scale data for model construction and validation (Wild-Allen et al. 2018).

Hydrodynamic, hydrologic and connectivity models

The hydrodynamic model (Herzfeld et al. 2018) is implemented on a fine-scale (600 m horizontal; 1–50 m vertical resolution) 3D grid of the Los Lagos Inland Sea, and nested within a regional shelf and global

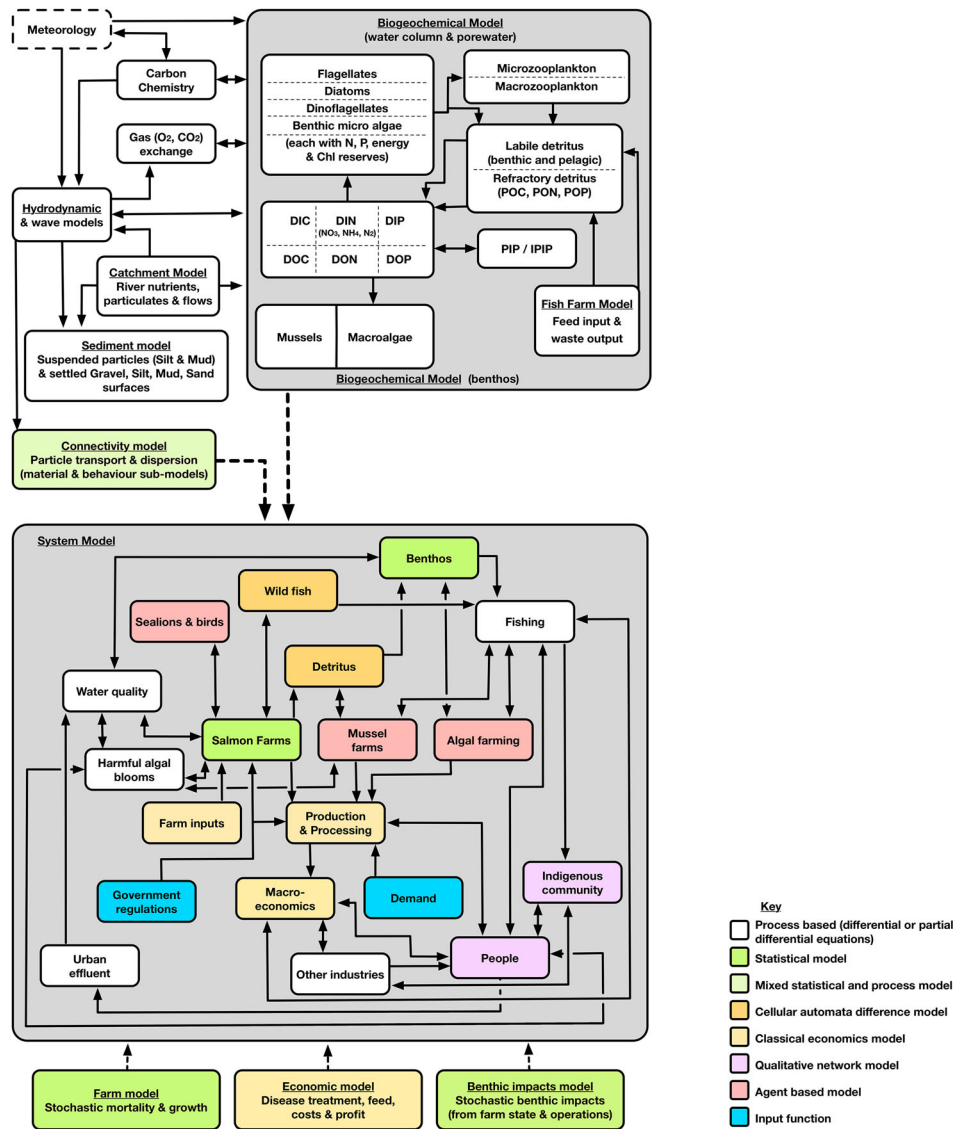


Figure 5. Schematic showing components of environmental and systems models colour-coded according to modelling approach.

ocean (BLUElink, Oke et al. 2008) model, to allow for accurate inshore propagation of circulation and water properties. Atmospheric fluxes are computed from the ACCESS-G global meteorological model.⁶

Daily river discharges for the 22 major river catchments in the region (Aryal et al. 2016; Aryal 2018) are simulated using the GR4J rainfall runoff model (Perrin et al. 2003) with a snow component (Nepal et al. 2017). Daily precipitation, evapotranspiration, minimum and maximum temperatures and river flow data, available for four catchments from the CAMELS-CL climate dataset⁷ (Alvarez-Garreton et al. 2018), were used to calibrate and validate the runoff model which was then used to derive the freshwater flows for the other rivers across the region.

Simulations of surface elevation, temperature and salinity were compared against observations from tide

gauges, moorings and field campaigns (Figure 6). Overall, the hydrodynamic model shows good agreement to available observations and can be considered a suitable platform to investigate system characterisation or drive transport for biogeochemical or sediment transport models. The hydrodynamic model can be used to generate flushing times, residence times and statistical distributions of passive tracers to assist with assessing connectivity within the domain. As an example, Figure 7 shows how a tracer released at different locations in the model domain (east, west and at multiple points) is rapidly transported through the system.

The connectivity tool CONNIE3 (CONNectivity InterfacE v3: www.csiro.au/connie/) combines currents generated by the regional hydrodynamic model with particle tracking techniques to make statistical estimates of exposure risk and flushing rates. It can be used for

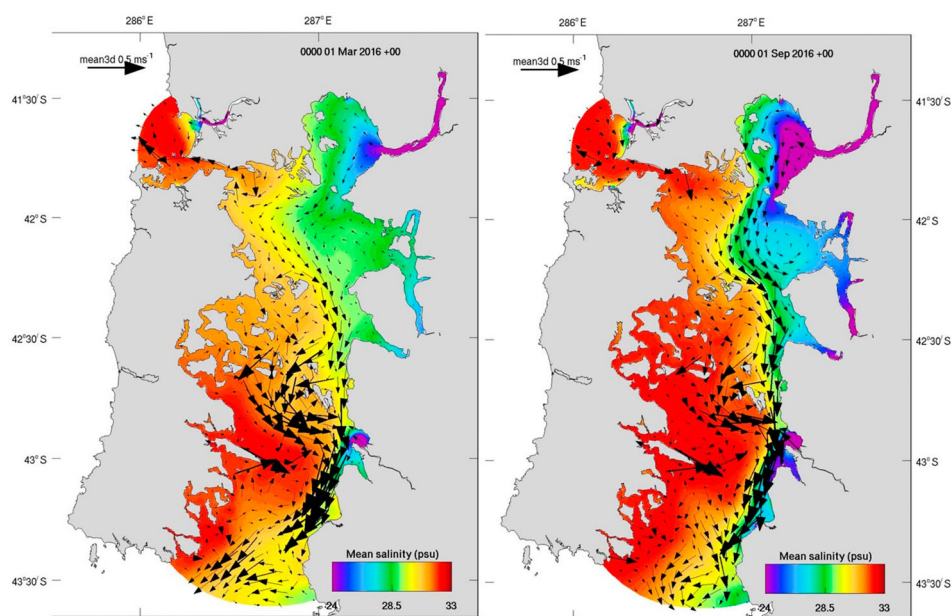


Figure 6. Hydrodynamic model output of the Los Lagos region showing mean (left) summer and winter (right) salinity with vectors representing surface velocity.

assessing the connectivity between regions or farm-to-farm – providing estimates of the dispersal of contaminants (e.g. nutrients, sediments, oil, debris) and particles e.g. through the Los Lagos region (Gorton and Condie 2018). CONNIE3 includes a range of biological behaviours, including horizontal swimming (constant or random), diurnal vertical migration, and accumulation within surface slicks. Preloaded behaviours (such as the life history and behaviour of *Caligus*) can be selected for substances and organisms of particular interest. For each model run particles are seeded within a user-specified source (or sink) region at a constant rate of 100 particles per grid cell per day over the user-specified

release period. This seeding rate adequately captures dispersal statistics, while maintaining relatively rapid computational rates. Following seeding, particles are tracked individually using a 4th-order Runge–Kutta ordinary differential equation (ODE) solver that linearly interpolates to find the horizontal velocity at the required depth and time. If the user specifies the release area as a source, then particles are tracked forward in time from the release; conversely, if an area is defined as a sink, then particles are tracked backward in time ending at the release cells. As an example, Figure 8 shows the potential dispersal of sea lice from the islands of the Gulf of Ancud.

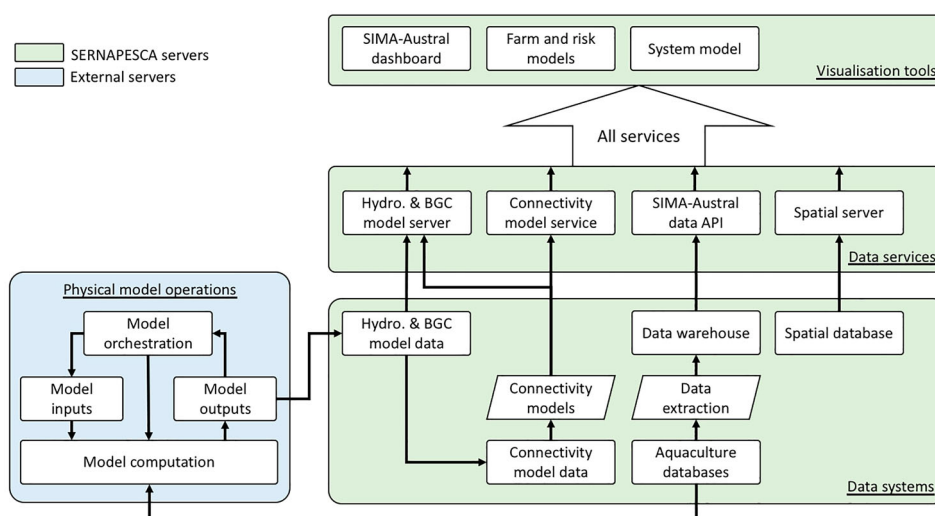


Figure 7. Schematic of the SIMA-Austral platform, which brings together data and models through a suite of data systems, data services and interactive visualisation tools.

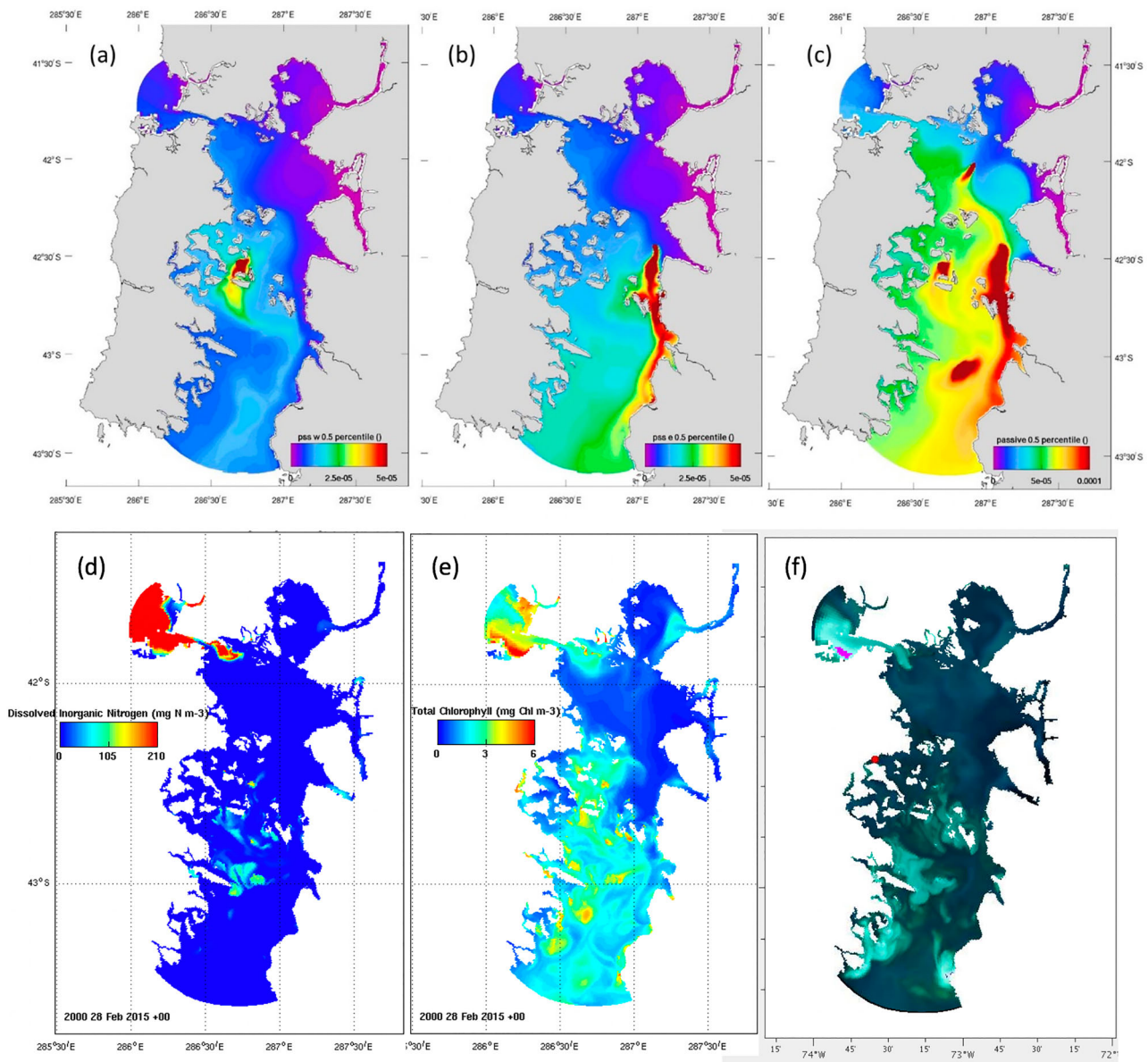


Figure 8. Example Environmental Model output showing (a) median distributions of tracer due (in kg m^{-3}) to the release of 1 kg s^{-1} flux into the surface at a western (a) and eastern (b) site and (c) four sites across the model domain; (d) surface dissolved inorganic nitrogen (e) total chlorophyll and (f) surface water true colour.

Sediment and biogeochemical models

The sediment transport model (Figure 5(a)) simulates the sinking, deposition and resuspension of multiple size-classes of suspended sediment (Margvelashvili 2018). Simulated spatial distributions of gravel, sand and mud have been compared with benthic sample data collected throughout the model domain and characterise the spatial footprint of catchment sediment loads entering coastal waters (supplementary material).

The biogeochemical model (Figure 5(a)) simulates the cycling of carbon, nitrogen, phosphorus and dissolved oxygen (e.g. Figure 8) through four groups of

phytoplankton (small, large, dinoflagellates, microphyto-benthos) plus benthic macroalgae, two groups of zooplankton (micro, meso), labile and refractory detritus and dissolved organic and inorganic nutrient pools (Wild-Allen et al. 2018). Micro- and macro-algae grow at a rate determined by access to dissolved nutrients (nitrogen and phosphate) and spectrally resolved light (Figure 8(c)). Fish farm waste discharge was derived from fish biomass at each farm location, a statistical Salmon growth model and assimilation efficiencies (Buschmann et al. 2006).

Sediment and nutrient loads from rivers are estimated from observations collated by Chile's Dirección General

de Aguas (DGA)⁸ and the Center for Climate and Resilience Research⁹ and nutrient loads from waste water were derived from data supplied by the Chilean Superintendencia de Servicios Sanitarios¹⁰ and the environmental information system of the Ministerio del Medio Ambiente.¹¹

An optical model integrates the absorption and scattering of incident irradiance from all dissolved and particulate substances in the model to determine the in situ light field and spectral sea leaving radiance. Simulated surface ocean colour can then be compared directly with remotely sensed products including true colour and algorithms for chlorophyll or CDOM. Model skill is assessed against available data from moorings are summarised in the supplementary material and detailed in Margvelashvili (2018) and Wild-Allen et al. (2018).

Data integration, informatics, reporting and visualisation

SIMA relies on databases, some internal to SERNAPESCA and some held externally by other government and industry organisations (Figure 7). Within SERNAPESCA, a number of databases have over time been developed but have limited inter-operability. These databases are primarily used to ingest and store data on aquaculture production, mortalities, treatments and vaccinations as well as operational information such as transport of fish and all other products required by the aquaculture industry. Additional databases contain information about the start and end of production cycles, fallow periods, as well as the stocking plans, company ownership, lease management, and information on non-salmonid aquaculture (mussels, algae and oysters), and environmental monitoring of the anaerobiosis of the benthos, and simple measures of water quality. The information contained in these databases is primarily collected and submitted by farm operators, although data such as environmental investigations and pathology reports are submitted by authorised consultants and laboratories. Structurally these databases are complex, due to the diversity of data providers and the functional modules allowing them to submit data. Subsequently, report generation and data investigation is limited by rigid workflows that required customisation of new functions.

The approach taken during the development of SIMA (Hodge et al. 2018) was to enable the internal and external systems to more effectively inter-operate by establishing a series of data services over the top of existing databases, spatial data systems and model data (Figure 10). The key additional services include a model service layer, a spatial data server, a Queryable data API and on-the-fly data processing services. This

approach provides the flexibility to add new products and services to allow ingestion into various end-user tools. These data services, sit behind the SIMA dashboard and bring together the various SIMA data products into an easy-to-use interface.

The SIMA dashboard is the primary user-interface that enables users to: (i) summarise data delivered from these data services at various spatial and temporal scales and (ii) to investigate patterns and detail in the data to help identify causes of specific events, plan responses and predict future events. The SIMA dashboard allows users to build decision trees to group data into different alert categories which are then available for end-users at suitable spatial and temporal scales in the form of maps, charts and tables. This functionality allows for improved operational intelligence allowing SERNAPESCA to proactively identify and manage issues.

Risk-based tools for tactical decision-making

While outputs from the models described above can be accessed individually from the SIMA dashboard, they can also be used and combined within a hierarchical risk assessment framework to provide risk assessments that can be used for tactical decision-making at the farm to regional scale, or for incident response. Such risk assessments can be undertaken throughout the aquaculture production cycle and is becoming an increasing focus for the development of approaches and tools for impacts assessments (e.g. Hallerman and Kapuscinski 1995; Naylor and Burke 2005; Taranger et al. 2015).

The SIMA risk framework has three tiers (Figure 4 (a)): (i) qualitative rapid assessment of issues allowing for a range of rapid strategic assessments (risk Level 1); (ii) data-driven evaluations completed within or around the production cycle (risk Level 2); and (iii) detailed quantitative analyses and modelling (risk Level 3), as required at different points in the planning and operational management cycles.

The Level 1 strategic risk assessments use expert-based ranking of impact factors that contribute to (primarily) epidemiological, environmental and production risks (Bustamante et al. 2018). The impact factors were derived from the literature (e.g. Gustafson et al. 2005, 2014; Mardones et al. 2009; Tapia et al. 2013; Gelcich et al. 2017) and from in-house surveys of staff of SERNAPESCA, experts from industry, academia and consultants. These Level 1 assessments provide a rapid overview of the sector, either as a whole or at regional scales where the smallest spatial scale is the neighbourhood of farms, termed Barrios.

At the farm-scale an analysis of the sanitary and environmental risk parameters through the production

and fallow cycle can be undertaken with the L2 Productivity-Susceptibility Analysis (PSA) tool (Bravo et al. 2018). The PSA aggregates variables (or attributes) into either a *productivity* (e.g. growth; mortality; vaccination; sediment anoxia; temperature; water velocity; connectivity; and marine traffic), or *susceptibility* (e.g. harmful algal blooms or HABs and sea lion incidence, water turnover, sea temperature and salinity, depth) score and represents these visually for each farm, or the overall risk distribution for all farms. The assessments are species-specific but are considered semi-quantitative as they do not eliminate the need for managers to decide upon the risk thresholds. Whereas farmers and regulators have little to no control – except by relocation – over the susceptibility attributes, the productivity variable can be used to identify feasible farming practices and management interventions that can reduce risk and include *inter alia*: changes to the stocking and harvest weight, fish density, smolt quality, and length of the fallow period.

The Level 3 risk assessment utilises the suite of SIMA models to provide risk support ranging from the operational farm-scale to regional long-term planning. For example, the epidemiological model can be used to explore how farm operations can be restructured to maximise growth and survival, while minimising disease loads and production costs. The whole-of-system model (Figure 4) can be used to evaluate (i) the efficacy of large scale changes to operating practices or management options (e.g. spatial arrangements, fallow periods, farm permit conditions); (ii) the interconnections within the system and the implications for social, economic and environmental carrying capacity; and (iii) the potential consequences of external shocks and scenarios (e.g. due to climate change, global market demand, growth of other local activities that may compete with aquaculture). This functionality can enable identification of future potential risks that are currently not typically considered by farm operators or regulators such as: declining social licence and increasing community tension around the role of aquaculture in the region's economy and social cohesion, external economic or climate shocks, emerging diseases, changes in zoning or broader land use change and development of the coastal region and waterways.

SIMA applications

Figures 1 and 2 summarise various use-cases of how SIMA can be used to address a range of issues associated with aquaculture. The following examples provide further detail around the application of SIMA for operational decision-making through to strategic planning.

Supporting strategic planning

Scenario analysis is an effective means of looking at potential system-level responses to changes in drivers, such as climate drivers or economic demand, as well as alternative operational practices or management options (Bueno and Soto 2017). As an example, scenario-based analyses for the Los Lagos region were defined by participants in a series of workshops held in May 2018 and are illustrative of how SIMA can be used to consider strategic or systemic risks.

Seven scenarios considered three that resulted in direct changes in salmon production from either a (i) single Harmful algal Bloom (HAB) event of 3 months duration, (ii) multiple (9) HAB events, or (iii) improvements in technology that reduced production costs. Another 3 considered shifts in local management that resulted from either (iv) stronger regulation of benthic habitats and resources, (v) protection of areas identified by Indigenous communities, or (vi) increased protection of marine resources and stricter environmental conditions. All were compared to (vii) the baseline Business as usual case (BAU) of 2017 production levels and management.

Each scenario was run by conditioning the model on the 2012–2017 period and projecting forward 20 years under the scenario conditions and run 100 times so that confidence intervals could be generated for each indicator. The final state of the system was judged on the final 10 years of the projection period relative to the BAU. Briefly, the results highlight a number of risks that face the aquaculture industry including:

- Under the BAU the profitability of the industry will likely become marginal as disease rates and treatment costs likely rise, but prices likely don't.
- Improved technological capacity can help mitigate these disease and economic risks and maintain profits and can simultaneously raise the reputation and realised quality of the product by reducing treatment and handling costs and lowering the footprint on the surrounding environment.
- Wild fish stocks are under pressure and will continue to decline (aggregate catch declining by 10–25%, as biomass declines by up to 30%) and this will in turn impacts upon aquaculture by: (i) increasing the likelihood of negative interactions between growers and large marine mammals such as sealions attracted to an 'easy' meal in the salmon pens; (ii) the depletion of wild mussel banks means that alternative livelihoods may not remain viable for many producers and (iii) increased tension among stakeholders in the region.

- Harmful algal blooms are a growing and serious risk in the region. The model showed that while the system can relatively rapidly recover from a single event, there is a threshold point (around one major event every 2–3 years) where the system begins to waver and more frequent events overwhelm many aspects of the entire socioecological system.
- Social tension is a significant risk to production under current system structure. Producers and regulators cannot afford to ignore this risk as it can undermine production (via blockage to ports or destruction of infrastructure) that can lead to economic losses. Circuit breakers around improving benthic stocks and opening up cultural tourism may help, but are unlikely to be a complete solution.
- This price sensitivity means that external market pressure (and loss of external demand) remains a source of ongoing risk for the industry. Large foreign markets currently exist, but if they begin to enforce more stringent requirements on what is considered acceptable product then the Chilean industry would find itself in trouble.

The SIMA Level 1 and 2 risk tools can be useful in determining the location of future aquaculture leases, identify locations or farming practices that are high risk in terms of environmental footprint and feedback on production conditions and carrying capacity and can be used for planning of appropriate stocking densities. As an example, Figure 4(b,c) depicts the results of farm-level Level 2 summary assessment undertaken at the end of 2017. In the PSA diagram (Figure 4(b)) each point is a farm and the resulting risk is the Euclidian distance to the origin. Farms in the lower left corner of the diagram are low-risk, as they that have low susceptibility and high productivity (vice versa for the high-risk farms in the upper right). The overall risk distribution (Figure 4(c)) shows that at the time of assessment, there was an almost normal distribution, where most farms are at an intermediate risk level (amber), while a few are low risk (green) and a smaller group are high risk (red). This assessment can be done quickly (5–9 days), and is best suited to risk minimisation during the production cycle and fallow period. It provides quantified estimates of background (fixed) risks – due to the location of leases, climate state and the like – as well as risk factors that can be actively modified – such as vaccination practices and stocking density. As these risks can include both direct risks (e.g. parasite loads) and indirect risks – such as benthic habitat status that can feed back on water quality and production conditions – the risk assessment addresses the multi-dimensional nature of

risk (across environmental, operational and animal health aspects) but also their interconnection.

Supporting operational decision-making and incident response

SIMA can support both industry and regulators to make informed operational decisions relating to production, treatment and management actions. For example, the Environmental Model output of near real-time hydrodynamic and biogeochemical conditions (Figure 8(d–f)) can identify whether prevailing oxygen, temperature and other environmental properties are suitable for

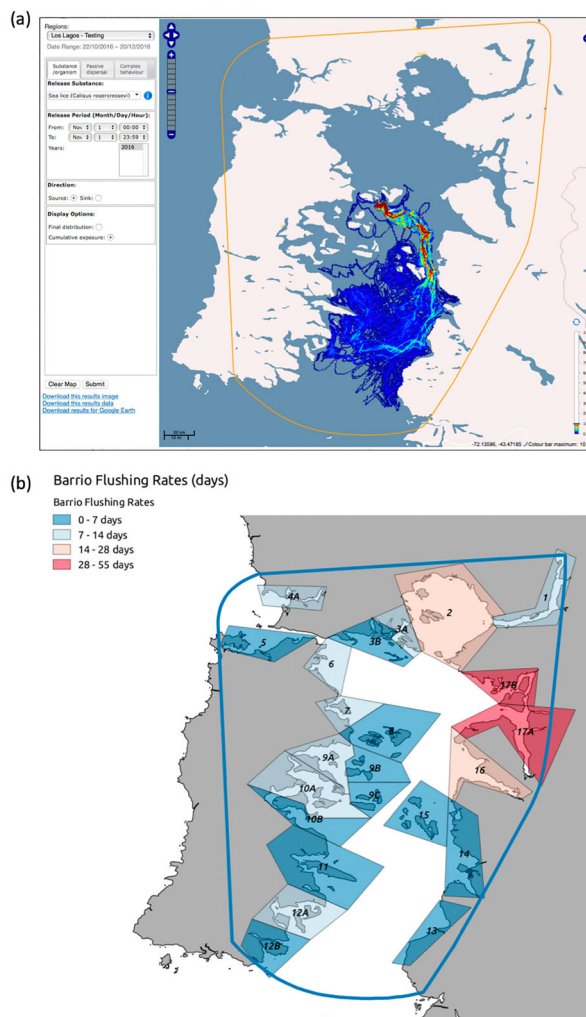


Figure 9. (a) Example of output showing modelled dispersal of sea lice released from a central-eastern island of the Gulf of Ancud in the Los Lagos Region over the period October to December 2016. Dark red indicates more than 10% of the release passed through the grid cell, green 40–60% and dark blue less than 10%. (b) Computed flushing timescales for barrios in the Los Lagos Region. These equate to the average time for concentrations within a barrio to fall to $e^{-1} = 0.368$ of their starting value. Longer flushing times typically increase the risk of contaminant accumulation and associated deterioration in water quality.

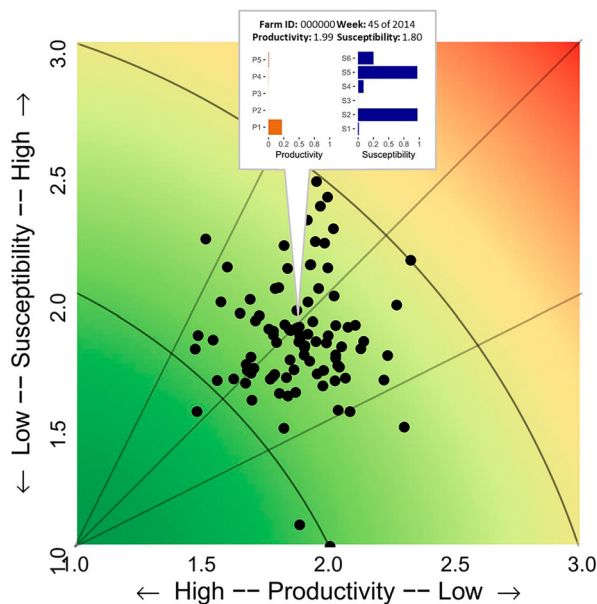


Figure 10. Two examples of operational outputs of the Productivity-Susceptibility risk analysis (PSA) for individual salmon farms from Los Lagos region at week 45 of 2014. (a) Biplot of the PSA where each dot is a production farm. The pop-up shows the normalised contribution of productivity (P1-P5) and susceptibility (S1-S6) attributes to the overall risk. [Attributes legend: P1 = fish density; P2 = fish weight at harvesting; P3 = fish weight at stocking; P4 = mortality by discard; P5 = mortality due to diseases; S1 = hydrodynamic connectivity with regards to other farms; S2 = average current speed; S3 = mortality due to predation (birds and sea lions); S4 = residence time of the sanitary neighbourhood; S5 = salinity; and S6 = temperature]. (b) The overall risk distribution for all salmon farms from Los Lagos region.

production or whether any potential negative consequences may need to be mitigated by changed operational behaviours, such as changed feeding patterns or early harvest.

A number of the *SIMA* tools can be used to look at the different aspects of disease transmission and risk mitigation. The Environmental Model climatology can be used for regional planning, to look at the likelihood of transmission between locations (i.e. production centres) and in near real time for incident response. Likewise, CONNIE can be used in a more accessible and visual way by users to consider the likely footprint of potential transmission (or potential sources) for an outbreak and to define and run scenarios with minimal training (Figure 9). This allows for the practical exploration of a range of practical applications, including risks of pathogen exchange between leases. Both the Environmental model and CONNIE can be used to address other issues including identifying impact zones around aquaculture leases associated with the dispersal of fish faeces and nutrients or for contaminant spills likely dispersal or source attribution (Condie et al. 2012).

A different form of modelling allows for consideration of dynamics within neighbourhoods. The statistical epidemiological ‘farm-scale’ model can be used to assess the risk of spread or intensification of infection given the current infection profile of a neighbourhood, the species mix and farming practices (Richards and Fulton 2018). Cumulative survival risks and levels of production can be forecast, combining multiple sources of mortality, and by linking with a simple economic model the implications for costs of production and expected returns can be assessed (Figure 10). This in turn, allows for consideration of how modified mortality rates, disease risks and farming practices can influence industry economic profitability and efficiency.

Discussion

Operating challenges and lessons learned

Traditionally regulation and operational management of salmonid aquaculture in Chile has principally focused only on control of disease and this reflects the fact many SERNAPESCA employees have a veterinarian background and, in some regions, outnumber the regional medical doctors (Barrett et al. 2002). The reality of aquaculture production in Chile and globally is changing, however. Through the 3-year development of *SIMA*, the topics considered in the joint collaboration between scientists and SERNAPESCA staff have evolved to consider a broader range of environmental, economic, social and cultural factors affecting the production system that can in turn affect the Industry and the decisions that need to be made at strategic and tactical levels of operation.

The approach to data has also evolved. Transitioning from a bottom-up desire to ‘integrate’ various data holdings (and simply make them more internally visible) to an appreciation that decision making requires a thoughtful process. In particular, starting with the decision to be made and working back to the data/information required to enable that decision. As a result, the data access needs have expanded to encompass a wider range of data, often held by other government agencies or by the Industry. In turn, this has required much greater collaboration between all the partners and across government, research agencies and Industry. This is an evolving process that has been a learning process for all involved; there have been both successes and mis-steps and much remains to be done. However, this shift does provide the potential for improved efficiency, economic potential and environmental outcomes by providing a means of moving away from reactive responsive management focus to forward looking planning and agile adaptive management.

The key issues now facing *SIMA* are the operational maintenance of *SIMA*, particularly ensuring a sustainable and harmonised observational infrastructure to support near real-time reporting and forecasting of environmental conditions.

Future development and application

The shift to the green narratives and the proactive use of a systems perspective and near real-time data delivery has (at least temporarily) provided countries such as Norway with a market advantage (Fløysand and Jakobsen 2017; Asche et al. 2018). As Australian producers struggle with environmental challenges, largely due to climate (Hobday et al. 2008) and increasing cumulative pressures on coastal systems (MacDonald 2000; Sanchez-Jerez et al. 2016), they too are looking to system-based decision support tools to assist their operational sustainability (Leith et al. 2014). Chile faces a more complex situation – where the industry is locked into a reactive model and needs to transform operations to a more proactive position.

The *SIMA* platform delivers the combination of short-term data needs and structured production and long-term planning tools. While the technological components are readily adaptable to new locations, further work will be needed to tailor the overall approach to the individual conditions in each new location. This is in part because of system-specific aspects of monitoring and indicator performance (a well-known issue within sustainable fisheries; Shannon et al. 2014; Shin et al. 2018), but also because there is a degree of co-development in the approach – without which it is likely that key contextual components (particularly issues associated with behaviour and social licence; Alexander et al. 2016) will be missed and that acceptance and uptake of the tool will not reach its full potential.

The Blue Economy is seeing a growing list of marine users, the majority of which have similar information needs (tactical and strategic) to aquaculture. It is relatively straightforward to adapt the *SIMA* platform to other industries within the Blue Economy – such as fisheries, mining, transport, and tourism. Indeed, the intellectual concepts underlying many of the structural components of the risk assessment framework in *SIMA* are inspired by previous work in fisheries (e.g. Hobday et al. 2011), or draw on the same model types and philosophies as used in fisheries (Fulton 2010; Plagányi et al. 2014) or integrated coastal management (Fulton et al. 2015). However, similarly to translating *SIMA* to a new aquaculture implementation, modifications would be needed to match the platform to the socioecological conditions

and specific user needs in any new application, whether in a new location, or for a new user/industry type.

International significance

Internationally, the demand for better information to manage – operationally and strategically – the aquaculture industry is growing. The global momentum on SDG implementation has also framed some of this discourse on the future sustainability of aquaculture, as has the mainstreaming of the ecosystem approach to aquaculture (EAA), championed by the FAO and others. We believe that *SIMA* is a significant operational step towards the operationalisation of EAA and to supporting the achievement of many of the SDGs. In addition to SDG 14, aquaculture is also highly relevant to nine other SDGs and so governance of the industry should be broadened to include not only conservation of resources, biodiversity and the environment, but also recognition of the social agency, well-being and livelihoods of people working in the sector and the contributions to interconnected global agendas, such as for food security, nutrition and trade (FAO 2018b). In this regard there is also close alignment with GEO Planet which focuses on connecting stakeholders with available data and products, working with stakeholders to develop decision support tools and identifies sustainable aquaculture and fisheries as one of its key themes (Smail et al. 2019).

The growing magnitude of interactions of aquaculture with other aspects of coastal and marine systems means that the flow-on effects of its activities are drawing increasing attention. These effects are many-fold, going beyond the traditionally considered environmental effects there are also the perceived acceptability (or otherwise) by regional communities of aquaculture operations (i.e. social license). This means there is a growing need for well-informed decision making locally – to avoid undesirable socioecological outcomes, but also as a basis for informing decisions by international bodies (e.g. the Aquaculture Stewardship Council, Best Aquaculture Practices) and for assessing the effectiveness of policy interventions. *SIMA* has a role in this via reporting, risk assessments and planning support.

Similarly, the risk and modelling tools could be re-adapted for new locations. The system level tools can also be immediately turned to larger scale regional planning, as they already integrate the key ecological features and major land and seascape users of the region(s). The functionality of *SIMA* is particularly important for regions with impending expansion of the industry, such as the Magallanes region of southern Chile. Here, *SIMA* can potentially play a role in better planning the siting of aquaculture and defining its various carrying

capacities, and ensuring this development is compatible with other uses in the region.

While many countries don't have the capacity to implement a project of the scale of SIMA the modular and open source approach allows some components – particularly the informatics and visualisation architecture – to be transferable to other regional-scale aquaculture industries. *SIMA* has inherited some code libraries from the models, informatics and visualisation codes used in the Australian *eReefs* initiative (see Steven et al., [in review](#)). It is pleasing to see that these inherited components have been expanded, refined and redirected in *SIMA* and that learnings gained from their use in *SIMA* can now be re-applied back in Australia; as the salmonid industry in Tasmania faces significant restructure and the development of a *SIMA* like information system may benefit the future management of the Industry there.

Conclusions

Development of scientifically robust information services, risk assessment and predictive operational and strategic planning tools at relevant spatial and temporal scales is critical for supporting evidence-based aquaculture production and sustainable management. Without such information environmental and other risks associated with ongoing production and any new proposed developments cannot be dealt with in a rigorous way. Timely, accessible information is an absolute necessity for supporting the regulatory agencies in ongoing management of existing and proposed aquaculture operations. The *SIMA* tools outlined here can be used to provide a detailed understanding of current status and trends, as well as likely and actual interactions between aquaculture production (primarily salmonid farming) and the surrounding system. This includes the receiving environment (biodiversity, abundance and biomass, water quality, sediment characteristics), but also the broader human system too. In turn, this information can be used to evaluate both how changes in the industry (such as expansions) may affect the system, including the Industry, but also to set and evaluate regionally appropriate production reference points, environmental thresholds and adaptive management practices.

Even with the best available information, success is still critically dependent on the capacity of the users. The correct governance must be in place for uptake, particularly as you step beyond single sector comparisons to cross departments (Smith et al. 2017). Boundary organisations are bodies that may have an increasing role to play as industries cut across increasing number of sectors and regulatory bodies.

Regardless of who takes on the role, the speed of change currently occurring as a result of climate change and the expansion of the blue economy means that management must move from reactive to proactive management for it to successfully implement effective adaptive management (Alderman and Hobday 2017). Combining such a shift in focus with effective information systems, such as *SIMA*, can support the kind of transformation in the industry that is needed to keep it healthy and productive in the context of a rapidly changing marine socioecological environment.

Notes

1. Sistema Integrado de Manejo para la Acuicultura Austral de Chile.
2. Access to best-practice epidemiology and sanitary procedures developed as part of *SIMA* are also available, but not discussed here.
3. A production cycle (typically 12–18 months duration for Atlantic salmon, shorter for other species, is dependent on the geographic region) and begins when the salmon smolt are transported to offshore pens and ends when they are harvested as adults.
4. Agrupación de Concesiones Sanitarias (ACS) or *Barrios* (neighbourhoods) http://ww2.sernapesca.cl/index.php?option=com_content&view=article&id=1220&Itemid=1009
5. Infraestructura de Datos Geoespaciales de Chile <http://www.ide.cl/>
6. <http://www.bom.gov.au/nwp/doc/access/NWPData.shtml>
7. <http://www.cr2.cl/datos-informacion-integrada-por-cuencas/>
8. Informacion Oficial Hidrometeorológica y de Calidad de Aguas en Línea <http://snia.dga.cl/BNAConsultas/reportes>
9. <http://www.cr2.cl/recursos-y-publicaciones/bases-de-datos/>
10. SiSS, Sistema de Información Territorial <http://geo.siss.cl/geonodo30/index.php?r=site/start&geoprofileId=41>
11. Sistema Nacional de Información Ambiental (SINIA) <http://sinia.mma.gob.cl>

Acknowledgements

Our gratitude to the Ministry of Economy of Chile and Fondo de Inversion Estrategica FIE who fund/support the development of *SIMA* Austral. We would like to express our gratitude to the entire SERNAPESCA team who collaborated and co-develop, as well as provide access to their main information system, knowledge and experience throughout the full development and delivery. We also greatly appreciate the support and collaboration of SUBPESCA, IFOP, Intesal, and the many people from Chilean aquaculture industry and the community who participated in workshops, discussion and that greatly contribute with their knowledge to the many parts of *SIMA* Austral. Support from the University of Chile in the operational stages of the *SIMA* Austral platform thanks to their hi-computing systems. Special thanks to Orlando Jimenez, Jose Miguel Burgos, Alicia Gallado, Marcela Lara, Yenny Guerrero, Rolando Ibarra,

R/V Khronos crew, Alicia, JM, Con, Andrea Bruna, Fabian Aviles, Stefan Gelcich and Rodrigo Estevez.

Disclosure statement

No potential conflict of interest was reported by the authors.

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